Transparent Piezoelectric Film Speakers for Active Noise Mitigation

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ABSTRACT

Noise pollution has a significant negative effect on psychological health and quality of life, and causes reduction in working and learning efficiency and even hearing loss under intensive and prolonged exposure condition. Passive noise mitigation using sound absorbing materials, micro-perforated panels and double layered structure have been used to improve the acoustic comfort in urban life today. These passive technologies are effective usually only at high frequencies and also cannot be applied when transparency is required in many application cases. In contrast, active noise mitigation technology can help to effectively suppress the low frequency noise. However, bulky and non-transparent electromagnetic speakers located at single or multiple points are typically used for active noise mitigation, which often limits global noise cancellation effect over a large area and has aesthetical acceptance issue. We have designed and produced transparent film speakers aiming at active noise mitigation application using piezoelectric polymer materials. The performance properties of our obtained transparent speakers are reported and their potentials for application in active noise mitigation systems are analyzed and discussed.

Keywords: Active noise mitigation, Transparent speaker, Piezoelectric speaker. I-INCE Classification of Subjects Number(s): 11.1.8, 38.2

1. INTRODUCTION

A major challenge for reducing noise transmission through windows is that the noise reduction is desired to be effective across all the window area while the window should still remain transparent and be aesthetically acceptable.

Double-glazed technology is one of main passive means to reduce noise transmission through window. However this technology is not satisfactory in low frequency range. Another problem of this approach is the lack of natural ventilation. Thus the air quality indoors is affected, or heavy use of air-conditioning systems leads to more power consumption.

Embedding active noise mitigation elements in windows has led in improved noise mitigation performance at low frequencies (1-4). For example, electromagnetic loud-speakers can be embedded within the air gap of the double glazed window. An outstanding problem is that such windows are bulky and costly, and not aesthetically acceptable. Voice-coil actuators could be discretely installed on window glass to generate canceling noise and realize active noise control particularly for low frequency noise (5). However these windows are not able to achieve uniform noise mitigation over the entire area, in addition to the affected transparency and aesthetics. The reduction of noise varies significantly at different locations. Use of many of such devices on window glass will greatly increase the overall cost and aggravate the transparency and aesthetics issues.

Recently transparent piezoelectric film speakers have been explored for replacing the conventionally used electromagnetic speakers in windows with active noise mitigation function (6). Various control algorithms have been developed to realize effective and uniform noise mitigation over window area using the transparent piezoelectric film speakers (7, 8). Although efforts have been made in literature to improve the sound pressure level of the piezoelectric speakers through various designs (9-11), there is big room to improve the speaker structure and characteristics for more effective noise mitigation. Piezoelectric speakers are often a type of piezoelectric uni-morph. Hence basic design rules of piezoelectric uni-morphs apply to the piezoelectric speakers. A piezoelectric uni-morph is often composed of a piezoelectric disk actuator clamped to a substrate, such as a...
metal plate. To maximize bending of the uni-morph, specific conditions should apply. Firstly, the ratio of piezoelectric disk actuator’s area to that of metal substrate should be optimized. In transparent piezoelectric speakers, this is relevant to the top electrode coverage, i.e. the ratio of the area of the top electrode deposited at the center of the transparent piezoelectric element \(A_t\) over the area of piezoelectric element \(A\) (inset of Figure 1(c)). Secondly, the thickness of substrate should be selected such that neutral line of the structure lies within the substrate. In this paper, we design and fabricate transparent piezoelectric film speakers using piezoelectric polymer materials. The effects of presence of a substrate as well as the top electrode coverage on sound pressure level of our obtained transparent piezoelectric film speaker are investigated through numerical simulation as well as experimental measurement. Other characteristics of the speaker including directivity and harmonic distortion, which are critical to active noise mitigation application, are evaluated.

2. NUMERICAL SIMULATION

In analogy to piezoelectric a uni-morph, optimal substrate thickness and top electrode coverage (area of piezoelectric actuator) of transparent piezoelectric film speaker were identified through numerical simulations with ANSYS (Version 15.0).

Structure of the speaker was composed of a top single walled carbon nanotube (SWCNT) electrode, a piezoelectric PVDF film with thickness of 110 \(\mu\)m, a SWCNT bottom electrode, a polyethylene terephthalate (PET) sheet as substrate and a frame to clamp the edges of the speaker (Figure 1(a)). Substrate thickness and top electrode coverage were varied to achieve the largest maximum displacement of the speaker under an applied DC voltage of 36 V; the larger the maximum displacement, the higher the sound pressure level of the transparent piezoelectric film speaker would generate.

Figure 1(b) shows the numerical simulation results for a 200×200 mm\(^2\) transparent piezoelectric film speaker with top electrode coverage of 100% and varying PET substrate thickness. A strong dependence of maximum displacement of the speaker on PET substrate thickness was found. The optimal PET substrate thickness for the speaker under simulation was about 65 \(\mu\)m after which the maximum displacement dropped.

To determine the optimal top electrode coverage, a transparent piezoelectric film speaker with PET substrate thickness of 65 \(\mu\)m and varied top electrode coverage was simulated, with results shown in Figure 1(c). The displacement of the speaker was strongly dependent on top electrode coverage. Compared to full coverage \(A_t/A = 1\), the maximum displacement of the speaker significantly increased (by a couple of orders of magnitude) with decrease of the top electrode coverage to 27%, and then dropped with further decrease.

Figure 1 – (a) Cross section view of the structure of transparent piezoelectric film speaker, and numerical simulation results for determination of (b) optimal PET substrate thickness (65 \(\mu\)m) and (c) optimal top electrode coverage for a transparent piezoelectric speaker with 110 \(\mu\)m thick PVDF.

Our simulation results suggest that performance of the transparent piezoelectric film speakers reported in literature (without substrate and with 100% top electrode coverage, hereafter called “conventional transparent piezoelectric film speaker”) can be significantly enhanced by optimization of design parameters. In the next section of this paper, a prototype of a transparent piezoelectric film speaker with the optimal parameters guided by numerical simulation (hereafter called “improved transparent piezoelectric film speaker”) will be presented, including the fabrication method and...
testing results.

3. FABRICATION OF TRANSPARENT PIEZOELECTRIC FILM SPEAKER

To fabricate the improved transparent piezoelectric film speaker, SWCNT thin film electrodes were constructed on a 110 μm thick PVDF film having dimensions of 200×200 mm². A suspension of SWCNT powders in DI water was sprayed on PVDF film using aerosol spraying process. Sodium dodecyl sulfate was used as a surfactant to stabilize the suspension. Bottom SWCNT electrode was formed continuously on one side of the PVDF film while top SWCNT electrode was patterned using a shadow mask to form the optimized top electrode coverage of 27%. The surfactant was then dissolved by merging the SWCNT coated PVDF film in DI water to reduce the sheet resistance of the electrodes. By controlling thickness of SWCNT electrodes, a sheet resistance of about 400 Ω/□ was achieved for the electrode layers.

After coating electrodes, the PVDF film was laminated on 70 μm thick PET transparent substrate using a transparent epoxy. After curing process of the PET/SWCNT/PVDF/SWCNT structure, the laminated structure was then clamped using a frame to form the improved transparent piezoelectric film speaker (Figure 2). For comparison, a conventional transparent piezoelectric film speaker with same dimensions as the improved transparent piezoelectric film speaker was also fabricated and tested.

Figure 2 – Photograph of the fabricated prototype of the improved transparent piezoelectric film speaker.

4. CHARACTERIZATION OF TRANSPARENT PIEZOELECTRIC FILM SPEAKER

Characterization of the fabricated speakers was conducted using PULSE Basic Electroacoustic software (Bruel & Kjaer) interfaced with a calibrated microphone, as summarized in Table 1. The microphone was placed 10 cm away from center of the speaker. The speakers were driven using an alternative voltage of 36 V.

<table>
<thead>
<tr>
<th>Operation Frequency Range (Hz)</th>
<th>50-20000</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPL (dB)</td>
<td></td>
</tr>
<tr>
<td>Bass (40-300 Hz)</td>
<td>40-75</td>
</tr>
<tr>
<td>Midrange (300-1200 Hz)</td>
<td>60-90</td>
</tr>
<tr>
<td>Treble (1.2-20 kHz)</td>
<td>70-85</td>
</tr>
<tr>
<td>THD (%)</td>
<td>4-65</td>
</tr>
<tr>
<td>Directivity</td>
<td>0-33</td>
</tr>
<tr>
<td></td>
<td>&lt; 1</td>
</tr>
<tr>
<td></td>
<td>Omnidirectional</td>
</tr>
</tbody>
</table>

4.1 Frequency Response

Frequency responses of the conventional and improved transparent piezoelectric film speakers were measured within the audible frequency range of 40 Hz-20 kHz and summarized in Figure 3. Sound pressure level (SPL) of the improved transparent piezoelectric film speaker ranged between 60-90 dB at frequencies higher than 300 Hz. Below 300 Hz, SPL was large only at a few resonance frequencies and ranged between 50-77 dB. Due to mechanical resonances, the frequency response did not exhibit a flat profile and a lot of peaks were present.
It was also found that the SPL of the improved transparent piezoelectric film speaker was significantly larger (by 10-30 dB) than that of conventional transparent piezoelectric film speaker with 100% top electrode coverage and without PET substrate. An exception was at the frequency of 75 Hz, where a resonance happened in the conventional transparent piezoelectric film speaker while there was no resonance for the improved transparent piezoelectric film speaker. The increased SPL of the improved transparent piezoelectric film speaker is due to the enhanced vibration displacement due to optimization of design parameters (partial top electrode and addition of substrate), as indicated by simulation.

![Figure 3 – Frequency response of the conventional and improved transparent piezoelectric film speakers.](image)

### 4.2 Directivity

Directivity of speaker is defined as angle of coverage of speaker output and is a characteristic of how a speaker sends sounds in different directions. For effective noise mitigation, it is desired that the speaker generates sound equally in all directions so that uniform noise mitigation within a space can be achieved. Directivity is characterized by measuring the SPL of speaker at different angles with microphone. The data is then plotted as a polar diagram to visualize the directivity of speaker. Polar diagrams of directivity of the improved transparent piezoelectric film speaker at different frequencies are presented in Figure 4. It is found that at all of the measured frequencies, the speaker generated almost equal SPL in all directions. Compared to most of the electromagnetic speakers which are highly directional (SPL is concentrated within and angle of ~60° or less), our improved piezoelectric film speaker is omnidirectional, which makes it promising for active noise control.

![Figure 4 – Polar figures representing directivity of the improved transparent piezoelectric film speaker.](image)
4.3 Harmonic Distortion

Harmonic distortion is caused by generation of harmonic vibrations in the speaker when it is being derived at a specific resonance frequency. Consequently, in addition to the originally derived frequency, the speaker generates harmonic sounds. As a result, during active noise mitigation, although the speaker suppresses the noise of the targeted frequency, it generates additional noise of higher order frequencies and hence noise mitigation will not be effective.

Harmonic distortion is quantified by total harmonic distortion (THD), the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. Figure 5 represents THD of the improved transparent piezoelectric film speaker measured at different frequencies.

At this stage, the fabricated speaker exhibits a large harmonic distortion at resonance frequencies below 900 Hz, which could reach 5 to 65% at certain resonance frequencies. Above 900 Hz, the speaker exhibits very low THD of less than 3%. Currently efforts are being made to reduce the harmonic distortion of the speaker. One method is tuning the driving wave form to suppress the harmonic vibrations. Our preliminary results show that by appropriately tuning the driving wave form, THD of the speaker at specific frequencies can significantly be reduced. Further investigations in this direction are ongoing.

![Figure 5 – Total harmonic distortion of the improved transparent piezoelectric film speaker.](image)

Although harmonic distortion of speaker is an important parameter in active noise mitigation, employing specific algorithms like adaptive active noise mitigation can help to compensate for the effect of harmonic noises.

The low directivity and satisfactory SPL of the improved transparent piezoelectric film speaker makes it promising for active noise mitigation applications. The improved transparent piezoelectric film speaker can be integrated with various window designs, with different shapes and geometries, as active noise mitigation element. The speaker can be produced over a very large area to cover the whole window to generate effective and uniform noise reduction.

5. CONCLUSIONS

A transparent piezoelectric film speaker composed of a SWCNT top electrode, a PVDF piezoelectric film, a SWCNT bottom electrode, a PET substrate and a frame was designed and fabricated. Numerical simulation revealed a strong dependence of displacement of speaker on substrate thickness and top electrode coverage. It was found that the optimal PET substrate thickness and top electrode coverage were 65 μm and 27%, respectively, for a 110 μm PVDF film. The improved transparent piezoelectric film speaker, fabricated with the optimal parameters guided by the numerical simulation outcomes, exhibited substantially improved sound pressure level (by 10-30 dB) compared to the conventional transparent piezoelectric film speakers without a substrate and with full top electrode coverage. Sound pressure level of the improved speaker was 60-90 dB at frequencies higher than 300 Hz and 50-77 dB at resonance frequencies below 300 Hz. The improved transparent piezoelectric film speaker was found to have a low directivity compared to electromagnetic speakers and could emit sound waves almost equally in all directions. Such characteristics make the improved transparent piezoelectric film speaker promising for active noise mitigation. One disadvantage of the obtained piezoelectric speaker for noise mitigation is the relatively large harmonic distortion at
frequencies below 900 Hz, which is to be addressed with ongoing efforts. The transparent speaker can be produced over a very large area to cover the whole window with potential for realizing effective and uniform noise reduction.

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